

Questioning the recent observation of quantum Hawking radiation

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A recent article [J. Steinhauer, Nat. Phys. **12**, 959 (2016)] has reported the observation of quantum Hawking radiation and its entanglement in an analogue black hole. This paper analyses the published evidence, its consistency with theoretical bounds and the statistical significance of the results. The analysis raises severe doubts on the observation of Hawking radiation.

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I. INTRODUCTION

Observations of Hawking radiation [1] in the laboratory [2] seem to have been vexed with problems. The very first of such observations [3] — with intense light pulses in optical media, soon turned out to be inconsistent with theory [4, 5]. The observation of stimulated Hawking radiation of water waves [6] was replicated with a nearly identical set-up but better instrumentation, and found to be anomalous scattering with and without a horizon [7]. The demonstration of black-hole lasing in Bose-Einstein condensates [8] was recognised as a fluid-mechanical instability [9, 10], although the author disputes that [11]. Nevertheless, these attempts of observing Hawking radiation in the laboratory have been tremendously fruitful, because their scientific debate has significantly advanced the subject. One would have learned much less from a perfect experiment right from the beginning.

This paper analysis one of the latest experimental demonstrations of Hawking radiation, an article [13] that claims to have finally and fully verified Hawking's calculation [1]. However, as Carl Sagan put it, extraordinary claims require extraordinary evidence. This paper scrutinises the published evidence and the methods of obtaining it. In doing so, it does not ask whether Hawking radiation *can* be observed [12], but rather whether it *has* been observed.

The article [13] in question reports on an experiment with Bose-Einstein condensates that are brought into motion by optical forces. An analogue of the event horizon is formed when the flow of the condensate u exceeds the speed of sound c . Hawking's theory [1] applied to this case [2] predicts that the horizon creates sound quanta, phonons, from the fluctuations of the quantum vacuum. On each side of the horizon, the phonon population \bar{n} is expected [1] to be equal and Planck-distributed

$$\bar{n} = \frac{1}{e^{\frac{\hbar\omega}{KT}} - 1} \quad (1)$$

where $\omega = 2\pi f$ denotes the circular frequency, \hbar Planck's constant divided by 2π and K Boltzmann's constant. The temperature T is given [14] by the relative velocity gradient at the horizon:

$$KT = \frac{\hbar}{2\pi} \left| \frac{d(u-c)}{dx} \right|_{\text{horizon}}. \quad (2)$$

Furthermore, the quantum particles are predicted [1] to be produced in maximally entangled pairs — one phonon outside

the horizon, the other inside. As one of the Hawking partners is beyond the horizon, one could never hope to observe this entanglement on astrophysical black holes, but in laboratory analogues one could.

Hawking's Planckian prediction (1) is only valid in a regime of weak dispersion, as will be explained in Sec. II. The experiment [13], however, operates at the borderline between weak and strong dispersion, and the observed population distribution is clearly influenced by dispersion. Beyond a critical frequency, no radiation is measured. Yet the article [13] claims the observation of a Planck spectrum. Furthermore, the article [13] reports on correlations of Hawking partners beyond the critical frequency, where there are no particles, which is impossible, as Sec. III is going to prove, unless the data are statistically irrelevant, as shown in Sec. IV. Assumptions and bias in the data analysis are pointed out in Sec. V and conclusions are drawn in Sec. VI.

II. DISPERSION

In laboratory analogues c is dispersive: it depends on frequency or wavenumber $k = \omega/c$. A horizon is formed where the velocity u reaches the group velocity $\partial ck/\partial k$. Due to dispersion the horizon is no longer sharply defined: it depends on wavenumber as well. Hawking's Planckian prediction (1) is only valid in a regime of weak dispersion. Sound in Bose-Einstein condensates at rest obeys the Bogoliubov dispersion relation [15]:

$$c^2 = c_0^2 \left(1 + \frac{\xi^2 k^2}{2} \right) \quad (3)$$

where c_0 denotes the speed of sound for $k \rightarrow 0$ and the length $\xi = \hbar/(mc_0)$ quantifies the dispersion (ξ is also the healing length of the condensate [15]). In condensates moving with velocity profiles u , sound waves experience the Bogoliubov dispersion in locally co-moving frames for the Doppler-shifted frequency:

$$\omega - uk = ck. \quad (4)$$

Figure 1 shows measurements [13] of the wavenumbers in different regions of the condensate (taken from Fig. 3 of the article [13]). One sees that, inside the horizon, there is a maximal frequency ω_c for waves propagating against the current. This is a simple consequence of Bogoliubov's relation (3): as the

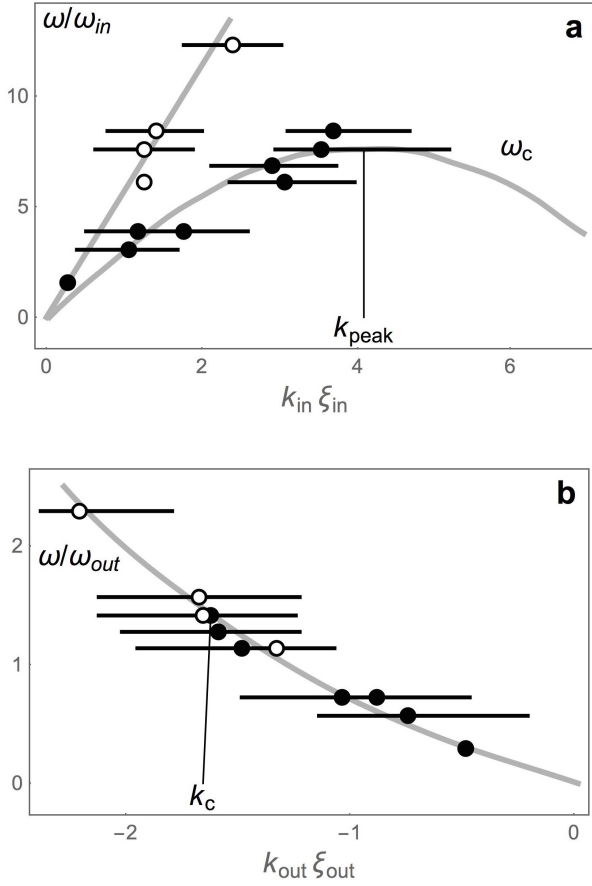


FIG. 1: Dispersion measurements. **a** inside the horizon: wavenumbers k_{in} corresponding to frequencies in units with $\hbar\omega_{\text{in}} = mc_{\text{in}}^2$ where m is the atomic mass; ξ_{in} is the dispersion/healing length of Eq. (3). The gray curves show the solutions of the dispersion relation, Eq. (4), with fitted parameters. One sees two branches, one (full dots) of Hawking waves trying to escape but not succeeding, the other (open dots when distinguishable) of waves propagating with the flow. At k_{peak} the Hawking waves are fast enough to reach the flow velocity and are no longer trapped; there is no horizon beyond the critical frequency ω_c . **b** outside the horizon: wavenumbers [16] versus frequencies (notation analogous to **a**). Here k_c is the wavenumber that corresponds to ω_c . The data points and error bars were taken from Fig. 3 of the article [13].

group velocity $\partial ck/\partial k$ of sound in the condensate increases with increasing k , there is a critical k_{peak} where the group velocity reaches the maximal velocity of the condensate in the experiment. Beyond the corresponding critical frequency ω_c there is no horizon. For $\omega \ll \omega_c$ one still gets a Planck spectrum of Hawking particles if the dispersion is weak, *i.e.* if ξ is significantly smaller than the characteristic length scale of the transition region where u turns from subsonic to supersonic [17]. As the Hawking temperature (2) is proportional to the relative velocity gradient at the horizon, most experimental analogues are forced to operate at the borderline between weak and strong dispersion, for maximising the particle yield. This is not necessarily a problem, but rather an opportunity to explore physics beyond Hawking's prediction (1).

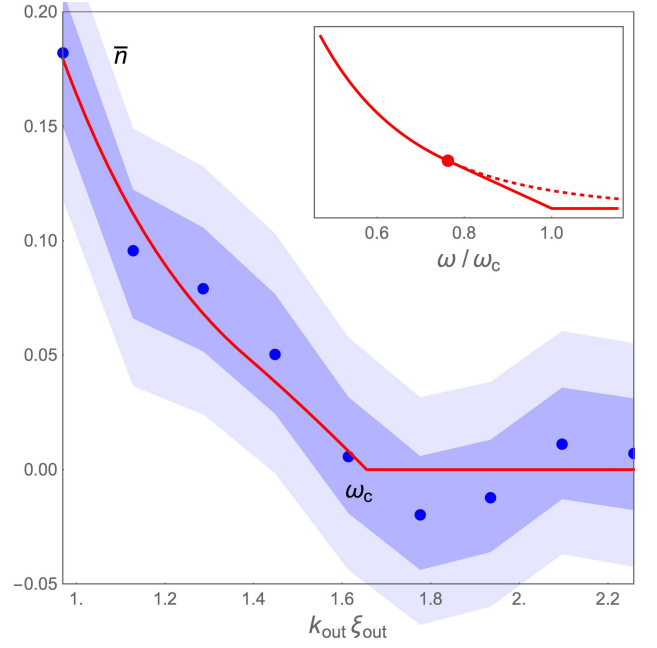


FIG. 2: Population of outgoing particles. The blue dots represent the phonon populations \bar{n} obtained from experiment [13] at wavenumbers k_{out} outside the horizon (notation as in Fig. 1). The points are surrounded by their vertical error bars; the dark-blue area represents 1σ and the light-blue area 2σ (where σ means the standard deviation). The data were taken from Fig. 5b of the article [13]. The population is zero within the error bars for the data points corresponding to frequencies beyond ω_c (Fig. 1). The red line shows a fit with a Planck curve linearly brought to zero at ω_c , as the insert illustrates. There the dotted line is the Planck curve continued beyond the red point of deviation. The data is consistent with the dispersion measurements (Fig. 1) and theoretical expectations, but the spectrum is clearly not Planckian.

Figure 2 shows the particle population versus wavelength inferred from measurements (taken from Fig. 5b of the article [13]). One clearly sees that beyond a certain wavenumber k_c the population vanishes within the error bars. According to the dispersion measurements shown in Fig. 1, the value of k_c agrees with the wavenumber outside the horizon that corresponds to the critical frequency ω_c . These findings are consistent with a Hawking spectrum that deviates from the perfect Planck curve (1).

The article states [13]: ‘the Hawking distribution at low energies is thermal in the sense that the population goes like $1/\omega$ ’. This refers to the low-frequency limit of the Planck curve, the Rayleigh-Jeans limit:

$$\bar{n} \sim \frac{KT}{\hbar\omega}. \quad (5)$$

However, in the experiment [13] the length scale of the transsonic region is comparable with the scale ξ of the dispersion. There is no guarantee that the constant T in Eq. (5) has the meaning of a Hawking temperature (2) that is proportional to the velocity gradient. For example, an infinitely steep step from subsonic to supersonic speed would, accord-

ing to Eq. (2), create an infinite Hawking temperature, yet due to dispersion the population is finite and behaves for small ω like Eq. (5) as well [18].

In the experiment, the Hawking temperature is inferred from fitting the particle population obtained outside of the horizon with a Planck curve that is linearly brought to zero at k_c (Fig. 2). The standard deviation of the fit, 0.025, lies within the error bar, 0.028, of the data, but a simple linear fit would give a standard deviation of 0.039, which is only marginally worse than the fit used to infer the Hawking temperature. No measurement of the velocity gradient at the horizon was reported [13]. Hence one cannot claim that the inferred T is indeed a Hawking temperature nor that the spectrum is Planckian, as was claimed [13].

III. ENTANGLEMENT

Hawking radiation is predicted [1] to be maximally entangled; each Hawking phonon that escapes from the horizon leaves a partner particle behind that drifts away on the other side. The experiment [13] attempts to verify this prediction. Figure 3 (taken from Fig. 6a of the article [13]) shows the correlations between the claimed Hawking partners inferred from measurements of the density–density correlations of the condensate. The figure shows no entanglement for $k_{\text{in}}\xi_{\text{in}} < 1.4$ inside the horizon that corresponds (Fig. 1) to $k_{\text{out}}\xi_{\text{out}} < 1.1$ outside the horizon where the agreement with the Planck curve (1) is best (Fig. 2). It does display entanglement for medium k , but then it goes on to show correlations beyond the critical k_{peak} where no Hawking particles were observed, which is impossible. One easily derives [19] from the Cauchy-Schwarz inequality for the correlation $\langle \hat{b}_H \hat{b}_P \rangle$ of Hawking (H) and partner (P) particles

$$|\langle \hat{b}_H \hat{b}_P \rangle|^2 \leq \bar{n}_H(\bar{n}_P + 1), \quad |\langle \hat{b}_H \hat{b}_P \rangle|^2 \leq \bar{n}_P(\bar{n}_H + 1) \quad (6)$$

where the \hat{b} are annihilation operators. The bounds (6) are valid for all quantum states, regardless of the specific values of the populations \bar{n}_H and \bar{n}_P . In particular, the correlation must vanish for vanishing \bar{n}_H or \bar{n}_P : no correlation exists without population, yet the article [13] shows correlations there (see the data reproduced in Fig. 3).

Hawking radiation is maximally entangled [17] in the sense that the populations of the Hawking partners are the same,

$$\bar{n}_H = \bar{n}_P = \bar{n}, \quad (7)$$

with \bar{n} given by the Planck spectrum (1), and the bounds (6) are reached:

$$|\langle \hat{b}_H \hat{b}_P \rangle|^2 = \bar{n}(\bar{n} + 1). \quad (8)$$

Relation (8) is called [13] the “Heisenberg limit” (although it does not originate [19] from Heisenberg’s uncertainty relation). The measured correlations (Fig. 3) appear to have reached the “Heisenberg limit” for large wavenumbers — beyond k_{peak} . Here the population curve \bar{n} in $\bar{n}(\bar{n} + 1)$ was convoluted with a Gaussian [21] (Fig. 4). The rationale for the

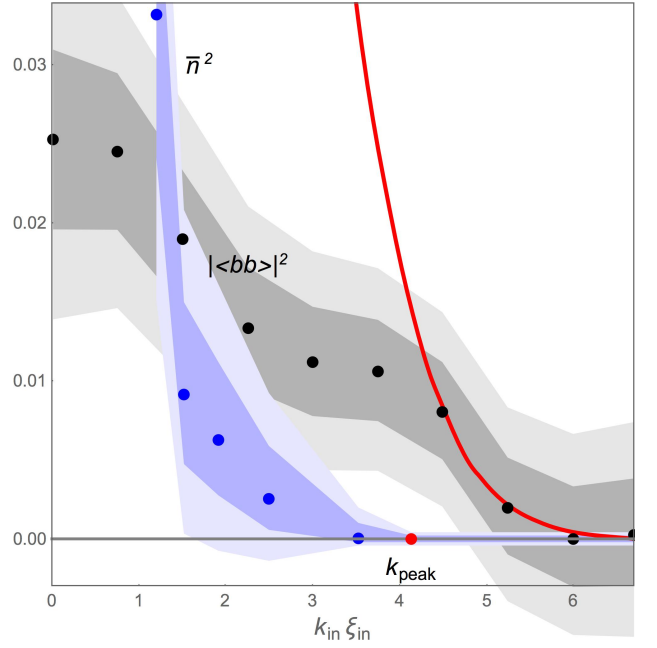


FIG. 3: Entanglement. The Hawking phonons are entangled with their partners if the correlations $|\langle \hat{b}_H \hat{b}_P \rangle|^2$ (black dots) lie above the populations squared \bar{n}^2 (blue dots), assuming the populations of Hawking and partner particles are the same. As in Fig. 2 the points are surrounded by their vertical error bars; the darker areas indicate 1σ , the lighter areas 2σ . The data (from Fig. 6a of Ref. [13]) are shown versus wavenumber k_{in} inside the horizon; the k_{out} of the populations (Fig. 2) are transformed via ω into k_{in} (Fig. 1). The populations vanish beyond k_{peak} (red dot) but not the correlations. The red curve shows the “Heisenberg limit” $\bar{n}(\bar{n} + 1)$ with \bar{n} obtained by convoluting the population curve with a Gaussian (Fig. 4).

convolution is the following: as the experiment lasts for a finite time τ the frequencies ω have the uncertainty $\Delta\omega \sim 1/\tau$. The dispersion curve $\omega(k)$ for phonons inside the horizon reaches a maximum at k_{peak} , and so $dk/d\omega$ tends to ∞ there; small uncertainties in frequencies result in large wavenumber uncertainties, which increases the error bars of k near k_{peak} (Fig. 1). There are two contributions to the error bars: the finite extensions of the observation regions and the finite observation time; for $k \sim k_{\text{peak}}$ the latter dominates.

Convoluting the population curve \bar{n} in $\bar{n}(\bar{n} + 1)$ with a Gaussian fits the last four data points of the correlation data (Fig. 3) if the standard deviation σ of the Gaussian is set to the constant 1.21 for k in units of $1/\xi$. This σ lies slightly above the maximal error bar 1.13 obtained from the dispersion measurements (Fig. 1). The agreement with theory for the data points at the tail of the “Heisenberg limit” is seen [13] as the strongest evidence for the entanglement of Hawking radiation.

However, the Gaussian smoothing with maximal error bar is only justified in the vicinity of k_{peak} , as the dispersion measurements show (Fig. 1). Taking the variation of σ into account [22] moves the curve of $\bar{n}(\bar{n} + 1)$ below the correlation curve (Fig. 4): the observed correlations violate the “Heisenberg limit” for large wavenumbers.

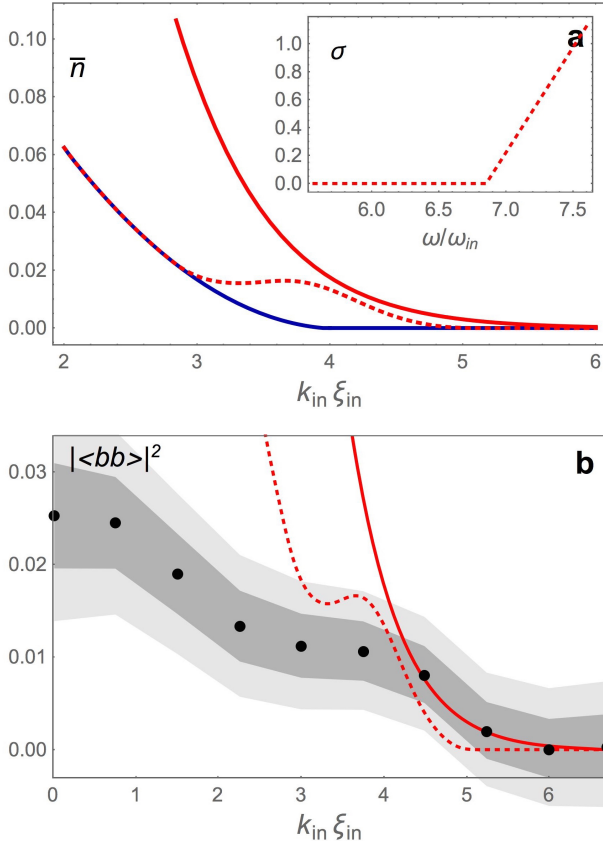


FIG. 4: Convolution. **a**: The fitted population curve (dark blue, from Fig. 2) is represented as function of $k_{\text{in}} \xi_{\text{in}}$ and convoluted with a Gaussian to produce the red curve for \bar{n} that gives the “Heisenberg limit” $\bar{n}(\bar{n} + 1)$ of Fig. 3 in agreement with the article [13]. The standard deviation of the Gaussian was set to the constant 1.21. The dotted curve shows the population curve convoluted with variable standard deviation σ displayed in the insert that reflects the actual uncertainty in $k_{\text{in}} \xi_{\text{in}}$ taken from the dispersion measurements [22] (Fig. 1). **b**: comparison of the “Heisenberg limits” $\bar{n}(\bar{n} + 1)$ with fixed (red) and variable (red, dotted) convolution with the particle correlations [13] (black dots, with uncertainty regions as in Fig. 3). Beyond the critical wavenumber k_{peak} the correlation curve tends to lie above the corrected “Heisenberg limit” (dotted line), which violates the fundamental bounds of Eq. (6).

For smaller wavenumbers, the correlations drop significantly below the prediction of maximal entanglement, Eq. (8). The article [13] states that here the Hawking pairs are less correlated than expected or are produced in smaller quantities. The latter, however, would contradict the population measurements. The two indications for Hawking radiation, the Planck spectrum for small wavenumbers and the alleged maximal entanglement for large wave numbers, are not consistent.

IV. UNCERTAINTIES

Perhaps these inconsistencies disappear if all uncertainties in the experiment are taken into account (Fig. 5). So far, it

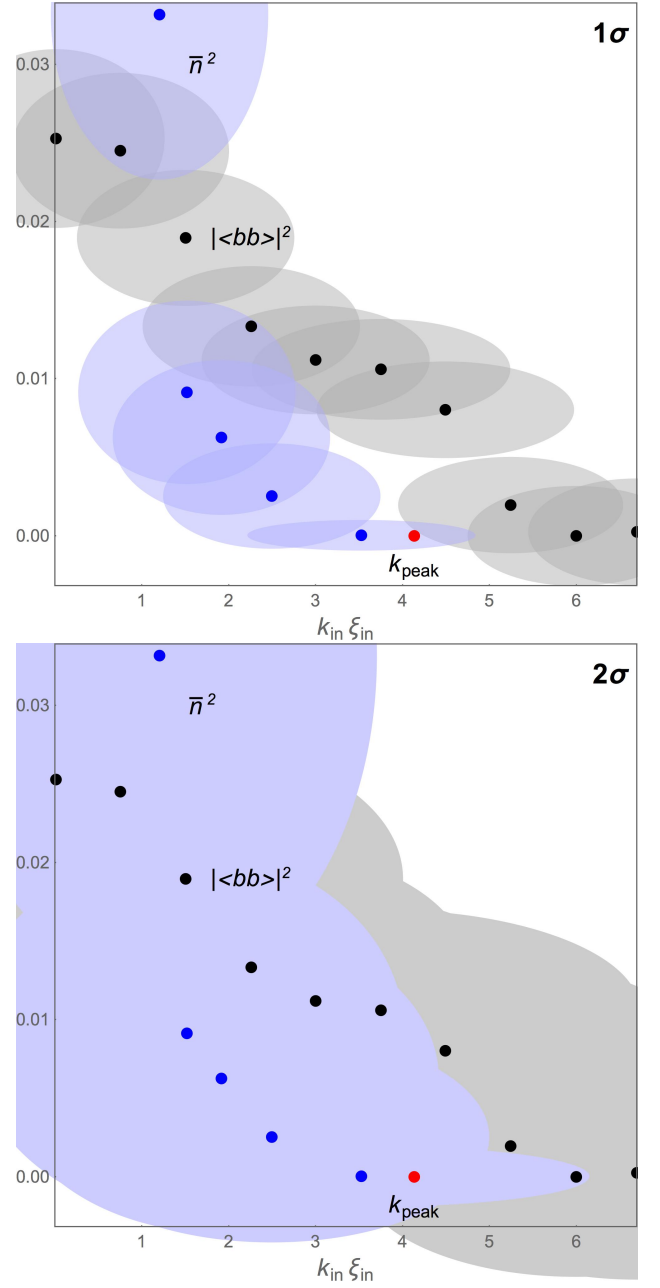


FIG. 5: Entanglement with full error bars. The data of Fig. 3 is shown with full error regions (ellipses). The uncertainties in the variables $k_{\text{in}} \xi_{\text{in}}$ are obtained from Eq. (9) and the dispersion measurements (Fig. 1) [16]. **1 σ** : the correlations $|\langle \hat{b}_{\text{H}} \hat{b}_{\text{P}} \rangle|^2$ (black dots, gray ellipses) are distinguishable from the populations squared \bar{n}^2 (blue dots, lightblue ellipses). **2 σ** : the curves are indistinguishable.

was assumed that the populations and correlations are functions of perfectly sharp wavenumber, except in the Gaussian smoothing of the population curve for fitting the “Heisenberg limit” $\bar{n}(\bar{n} + 1)$ to the tail of the correlation data. However, the wavenumbers do carry uncertainties (Fig. 1), primarily due to the finite sizes of the two observation regions (one outside,

one inside the horizon). Especially the correlations $|\langle \hat{b}_H \hat{b}_P \rangle|^2$ and $\bar{n}_H \bar{n}_P$ are sensitive to statistical errors, as they depend on two wavenumbers, k_H and k_P (k_{out} and k_{in} in Fig. 1). The correlation data is plotted as function of $k_P = k_{\text{in}}$ where k_H is related to k_P via the dispersion curves (Fig. 1) [16]. The error distribution of the wavenumber used for plotting is a convolution of the two individual error distributions. Assuming them to be Gaussian, the total variance σ^2 is the sum of the two individual variances,

$$\sigma^2 = \sigma_H^2 + \sigma_P^2. \quad (9)$$

One reads off the error bars from the dispersion measurements (Fig. 1) and interpolates them [16]. Figure 5 shows the result: if the uncertainties of the wavenumbers are taken into account the data of the correlations is only distinguishable from the data of the populations squared for one standard deviation, the two data sets melt into each other for 2σ . So, either one accepts inconsistencies in the data or the data become statistically insignificant.

V. ASSUMPTIONS

Additionally, assumptions were made throughout the data analysis based on the expectation of Hawking radiation. For quantifying the degree of entanglement, the correlation was compared with the population of only one of the Hawking partners (the one outside the horizon) and not also with the population of the other. The article [13] contains a hint [20] that also the population of the Hawking partners was measured, but the data were not published. For analysing the entanglement, it was assumed that \bar{n}_H and \bar{n}_P were the same. However, this was part of Hawking's prediction, Eq. (7), and cannot be taken for granted.

Assumptions were also made in the method [23] of obtaining the particle correlations from the experimental data. The correlations were inferred from subsets of the data integrated along lines parallel to a line of expected correlations (see Fig. 4 of the article [13]), a line found by optimisation. This method selects the Fourier-components of the density-density correlations evaluated within a subset of the data that would be consistent with the expected particle correlations. All other Fourier-components were ignored. Although this would give the Hawking correlations if they are there, it does not allow a comparison with the level of the other Fourier components: it does not discriminate between signal and noise, nor between signal and background.

The method of extracting correlations [23] involves another vital assumption: it assumes that only the Hawking partners are generated in accelerating the condensate beyond the speed of sound, but no other excitations in the fluid. As justification, the article states [13]: ‘the neglected terms represent correlations between widely separated phonons on opposite sides of the horizon with different frequencies.’

However, this statement contradicts the dispersion measurements [13]. Figure 1a shows the wavenumbers and frequencies for the two possible modes of excitations inside the horizon (represented by filled and open circles in the figure):

the Hawking waves attempting to travel against the flow and waves traveling with the flow. One sees that their wavenumbers and frequencies are similar. Neglecting the influence of extra excitations on the density-density correlation amounts to an assumption that has not been independently verified in the article [13].

VI. CONCLUSIONS

This paper has analysed the evidence for the observation of quantum Hawking radiation and its entanglement in the recent article [13] and found severe problems on several accounts. *First*, the observed spectrum of Hawking radiation is not Planckian, although the paper claims it to be. *Second*, particle correlations are observed without particles being present, unless, *third*, wavenumber uncertainties reduce the statistical confidence to one standard deviation, *i.e.* to insignificance. *Fourth*, no measurement of the population of Hawking partners was reported. *Fifth*, the method of inferring particle correlations from the measured density-density correlations relies on the expectation that Hawking radiation is present and nothing else. Overall, an unbiased, blind analysis of the data was not reported, which does not conform to the standards of claiming a discovery.

Instead of attempting to fully confirm Hawking's theory [1] in the laboratory, the experiment [13] may have missed discovering a different interesting phenomenon, like its predecessor [8–10]. A recent experiment [24] with water instead of a Bose-Einstein condensate has made a surprising discovery: hidden in the ripples of the water surface, the analogue of Hawking radiation was revealed and correlations between Hawking waves were seen. There the slight turbulence of the water played the role of the quantum vacuum, stimulating Hawking radiation. While classical fluids like water cannot show quantum entanglement, the situation is different in quantum fluids. Here quantum fluctuations other than the ones of the vacuum can create entanglement. For example, seeding the Hawking process [25] with a coherent state [25] does produce entanglement [26]. Such situations may mimic Hawking radiation in some aspects, but not in others, which, apart from statistical uncertainty, might explain the puzzling results of the article [13].

While the experimental data of the article [13] are valid, although incomplete, the conclusions and claims are not, especially the claim of having observed entanglement with a statistical confidence of $90/16 = 5.7\sigma$, which reduces to the order of 1σ on closer inspection. The 750 GeV bump in the LHC data had a statistical confidence of 2.1σ , but still turned out to be a coincidence [27]. One cannot claim that quantum Hawking radiation and its entanglement has been observed by the standards of a discovery. What has been observed is a matter of debate.

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- [21] The convolution of the Planck curve (1) as function of $\omega(k_{\text{in}})$ with a Gaussian would diverge due to the pole (5) unless it is cut off; here we cut it off for $k_{\text{in}}\xi_{\text{in}} < 0.05$.
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- [26] The process of Hawking radiation [25] transforms the initial annihilation operators \hat{a}_1 and \hat{a}_2 into $\hat{b}_{\text{H}} = \hat{a}_1 \cosh \zeta + \hat{a}_2^\dagger \sinh \zeta$ and $\hat{b}_{\text{P}} = \hat{a}_2 \cosh \zeta + \hat{a}_1^\dagger \sinh \zeta$ with $\tanh^2 \zeta = \exp(-\hbar\omega/KT)$. Suppose the initial state is $|\alpha\rangle_1|0\rangle_2$ with $|\alpha\rangle$ being a coherent state [25]. One finds that the final state is always entangled. However, in the article [13], it would only appear to be entangled for $|\alpha|^2 < \exp(-\hbar\omega/KT)$, as only then the correlation exceeds \bar{n}_{H}^2 . Note that $\bar{n}_{\text{H}} \neq \bar{n}_{\text{P}}$ here, which would still be consistent with the published data [13].
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